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What is the state of the art in energy and transport poverty metrics? A critical and comprehensive review

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ABSTRACT

This review investigates the state of the art in metrics used in energy (or fuel) and transport poverty with a view to assessing how these overlapping concepts may be unified in their measurement. Our review contributes to ongoing debates over decarbonisation, a politically sensitive and crucial aspect of the energy transition, and one that could exacerbate patterns of inequality or vulnerability. Up to 125 million people across the European Union experience the effects of energy poverty in their daily lives. A more comprehensive understanding of the breadth and depth of these conditions is therefore paramount. This review assessed 1,134 articles and critically analysed a deeper sample of 93. In terms of the use of metrics, we find that multiple indicators are better than any single metric or composite. We find work remains to be conducted in the transport poverty sphere before energy poverty metrics can be fully unified with those of transport poverty, namely the stipulation of travel standards. Without such standards, our ability to unify the metrics of both fields and potentially alleviate both conditions simultaneously is limited. The difficulties in defining necessary travel necessitate the further use of vulnerability lenses and holistic assessments focused on energy and transport services.

1. Introduction

Energy sits at the core of human and economic development. It enables the adequate illumination of homes, the proper and healthy cooking of food, the needed pumping of groundwater for food security, the refrigeration of vaccines, and many other services that are essential to even a very basic standard of living. Such services are often taken for granted worldwide, but the sobering truth is that much of the world resides in "energy poverty."

The term "energy poverty" commonly refers to the inability of a home or small business to afford an adequate supply of heat, electricity, or energy services (Bouzarovski and Petrova, 2015). Energy poverty is escalating everywhere, from Austria (Brunner et al., 2012), the United Kingdom (UK) (O'Brien, 2011), Hungary (Herrero and Urge-Vorsatz, 2012) to New Zealand (Howden-Chapman et al., 2012) and Japan (Okushima, 2017), due to the coincidence of rising fuel prices with decreasing household purchasing power. Such energy poverty typically results in inadequately heated houses, with a wide range of associated health impacts, including increased risk of respiratory and circulatory disease in adults, premature heart attacks in adults, asthma in children, thousands of excess winter deaths among the elderly, and increased risk of mental health illness and social isolation (National Audit Office, 2003) (O'Brien, 2011) (Rudge and Gilchrist, 2005).

Soberingly, the groups most vulnerable to energy poverty are low-income households with children, the elderly, the disabled, and people with long-term health conditions (Bednar and Reames, 2020). Most

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severely, energy poverty leads to "excess winter mortalities," quite literally killing people who go without essential heat. One report calculated 167,690 excess winter deaths from 2011 to 2017 in the UK, of which they attributed 50,310 to cold housing conditions, and of this, 16,770 to fuel poverty (Guertler and Smit, 2018). For comparison, the number of excess deaths over this period is more than the number of people who died from cancer in the UK in 2017 (World Cancer Research Fund, 2020). In cold American states such as Vermont, energy poverty results in more deaths each year than automobile accidents (Teller-Elsberg et al., 2016). Thus, energy poverty poses a significant problem for both the technical and policy worlds.

In parallel with the widespread nature of energy poverty, transport poverty is also a prevalent phenomena which may affect up to 90% of households (Lucas et al., 2016). We take transport poverty as the enforced lack of mobility services necessary for participation in society, resulting from inaccessibility, and or unaffordability, and or unavailability of transport (Lucas et al., 2016) (Mattioli et al., 2017) (Mullen and Marsden, 2016). Given that the effects of transport poverty include increased exposure to small and fine particulate matter (i.e., $PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2), particularly for the poor and marginalised, we should consider it no less deadly than energy poverty (General Consumer Council of Northern Ireland, 2001).

Historically, in engineering since the 1970s, particularly civil engineering and within the field of transport, poor accessibility and the resulting social problems posed to marginalised groups were well recognised as challenges. Indeed, the aim of much engineering work was to enable better transport and land use planning, aiming to enable more accessibility, enhance living spaces and to do so sustainably (Woodcock et al., 2007) (Meikle and Bannister, 2003). Whilst these challenges were well recognised, they were not conceptualised as distinct from deprivation or poverty more generally.

Recently in the social sciences, it has been postulated that energy and transport poverty are not distinct and have overlapping causes and links (Mattioli et al., 2017), (Martiskainen et al., 2019). The combination of research from both engineering and social science disciplines suggests to us that energy and transport together can manifest a double vulnerability for particular households (see Fig. 1) that may be able to afford neither, or make tough choices about which to prioritize (heat at home, or bus fares for school).

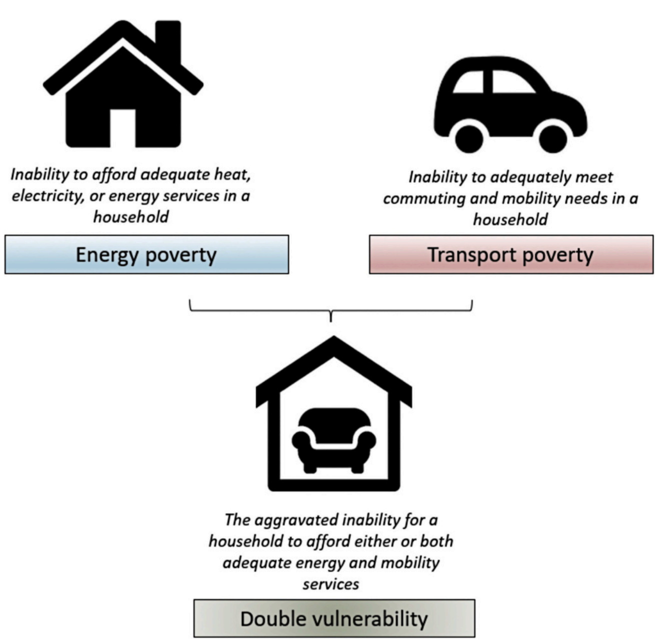

Fig. 1. Showing the double vulnerability inflicted upon households by energy and transport poverty.

Furthermore, as the energy and transport systems become further interconnected (as the low carbon transition progresses), a question that follows from this hypothesis is how are these conditions measured, and from which viewpoints do we consider them. This combination of social science and engineering considerations will form a starting point for aligning decarbonisation pathways with the Just Transition; by enabling decision makers in government, industry and society at large to make "just" choices regarding technology, economic and policy issues.

When considering the question of how these conditions are measured, it must be noted that despite the sheer economic, social, and public health importance of energy and transport poverty, metrics for estimating their scope and extent remain inconsistent, vary in quality, and are often disharmonized (Mahoney et al., 2020). Given the high range of estimates for the extent and depth of energy and transport poverty, we believe that how they are measured poses a serious concern for policy makers and the academy alike: the extent and depth of each issue will affect the extent and depth of proposed solutions in the built environment and policy spheres.

In this state of the art review, we undertake an extensive bibliometric and content analysis of 1,134 papers, analysing a deep sample of 93 papers and items of grey literature. We analyse the authors in this space, journals, and key terms for their trends. Subsequently, we analyse key metrics in energy and transport poverty for their utility and how they might be united. We conclude this paper with suggestions for uniting the measurements and how to arrive at a more comprehensive assessment of these conditions. We believe more comprehensive assessments will be vital, particularly as the energy and transport systems become more unified, such that these assessments can be put to use in order to alleviate these conditions and improve the quality of life of millions.

2. Reviewing, defining and estimating "poverty," "energy poverty", and "transport poverty"

There is no universal definition of poverty, but broadly speaking, definitions are concerned with an individual's access to and ability to afford different services. According to the Joseph Rowntree Foundation, "*Poverty means not being able to heat your home, pay your rent… because of your financial circumstances. The constant stress it causes can lead to problems that deprive people of the chance to play a full part in society*." (Joseph Rowntree Foundation, 2020). An excerpt from the United Nations definition is that poverty constitutes a "*lack of basic capacity to participate effectively in society*" (Gordon, 2005). Indeed, the concept of poverty as a deprivation of a certain requirement has been applied to many areas of social science and beyond.

The term energy or "fuel" poverty first emerged conceptually in England during the 1970s as fuel poverty and gained recognition within academia and social rights campaigners in the same decade (Marchand et al., 2019). Years later, in 1991, Boardman tried to conceptualise this idea under the premise that the fuel poor were those unable to heat their homes to certain standards of warmth (Boardman, 1991). That is to say, fuel poverty as a condition was not historically considered as a condition separate and distinct from "poverty" until 1991. Transport poverty, however, is a much more nebulous term with multiple components not limited to the affordability of transport (Lucas et al., 2016) but also entails other social and material elements (Martiskainen et al., 2021).

In France, fuel/energy poverty is referred to as "précarité énergétique" (Observatoire national de la précarité énergétique, 2016). If we translate précarité literally to precarity or precariousness, we mean "*the condition of being likely to fail or get worse*" or "*the dangerous state of not being in a safe position or not being held in place firmly*" (Cambridge Dictionary, 2020). This concept of not being in a safe position results from the inability to secure necessitated energy services in the home (Bouzarovski and Petrova, 2015).

Thus, when we discuss fuel poverty and transport poverty, we are not concerned with the conditions themselves per se, but rather, their adverse physical and social consequences. That is to say we are concerned with the consequent *inequity* that results from these conditions. It is with this lens of inequity, of both provision of fuel/energy and transport, and the inequity of consequential outcomes that we examine fuel/energy and transport poverty in this review.

Energy and fuel poverty have long been known to adversely affect the health of populations living in these conditions. In Europe, for instance, research has shown a high incidence of poor physical and mental health among the most energy poor households. The inequality in health outcomes is most acute in otherwise relatively equal societies (Thomson et al., 2017b). Thus, we can see that when we control for other factors to the greatest extent possible, fuel poverty indeed adversely affects public health. Further to mental and physical health, fuel poverty has been linked to household debt, low educational attainment, and poor housing quality. These factors can be mutually reinforcing, (e.g. the link between poor mental health and poor educational attainment) (Baker et al., 2018).

In the European Union (EU), energy poverty remains a thorny problem, with research estimating that in 2009, between 50 and 125 million people were living in these circumstances (EPEE Consortium, 2009). While in the UK alone, more than 10% of English households were in fuel poverty in 2018 (approximately 2.4 million households) (Department for Business, Energy, and Industrial Strategy, 2020).

As for transport poverty, some studies indicate that it is an issue that affects anywhere between 10 and 90% of all households, depending on which definition is used and which country is considered (Lucas et al., 2016). For example, in England, more than 1.5 million people are affected by this issue (Sustrans, 2012). On top of that, the report from the General Consumer Council of Northern Ireland (2001), highlights the inequity associated with and caused by transport poverty. These include, for instance, restricted access to employment, increased likelihood of exposure to air pollution, and increased difficulties faced by the disabled. This theme of disadvantage or exclusion was continued by the social exclusion unit, stating that people may find services (work, learning, healthcare etc.) inaccessible as a result of social exclusion, that transport disadvantage can seriously compound this social exclusion, and that the negative externalities of road traffic disproportionately impact those who already face social exclusion (Social Exclusion Unit, 2003). This consequent inequity has elsewhere been noted to also carry over into more negative subjective wellbeing (Churchill and Smyth, 2019). Furthermore, as with other issues related to vulnerability and inequity, there is a gender divide when looking at transport poverty. Research identifies that issues related to transport access and mobility disadvantage women more than men due in part to the higher proportion of household tasks they are expected to perform under current societal norms (Turner and Grieco, 2000). Additionally, men are more likely to own cars, and women often have more complex travel patterns, which results in women not only using public transportation more frequently but also spending greater time and money on it (Perez, 2019).

As stated in the introduction, it has recently been postulated that energy and transport poverty are related conditions (Mattioli et al., 2017), (Martiskainen et al., 2019). Lucas reiterates earlier work in an editorial to state that transport poverty is often not only a transport problem, and as such, not only does it have wider effects, but it also requires solutions that go beyond the realm of transport alone (Lucas, 2018). It is with this in mind that we seek to understand the reconciliation of metrics in fuel and transport poverty.

We have conducted a systematic literature review to determine what is the "state of the art" in fuel/energy and transport poverty metrics. Secondary questions asked are who studies fuel/energy and transport poverty, where these researchers are located, and what we can determine from this i.e. we wish to determine which disciplines dominate these areas and what this tells us regarding solving these problems. To identify relevant studies a literature review was conducted using the Web of Science database. Subsequently, we conducted a bibliometric analysis to determine patterns within the literature. Next, key studies were identified and their content analysed, alongside prominent grey literature in each area.

3. Research design and bibliometric analysis

This review adopts the definition of fuel/energy poverty created by Bouzarovski and Petrova with a view to unifying the fuel and energy poverty literature. Thus, we consider fuel poverty as "*the inability to secure materially and socially-necessitated energy services, such as heating a home or using appliances*" (Bouzarovski and Petrova, 2015). Other attempts have been made to reconcile the differences such as Li et al., 2014, but we judge these to have not been sufficiently distinct or practical (Li et al., 2014). Typically, where "energy poverty" is studied in the literature, it refers to poverty of access to energy e.g. lack of rural electrification in developing nations. But there are often instances, e.g. occurrences in the United States of America (USA) context where energy poverty follows the definition outlined above.

We consider transport poverty to be the enforced lack of mobility services necessary for participation in society, resulting from the inaccessibility, unaffordability or unavailability of transport (Lucas et al., 2016) (Mattioli et al., 2017) (Mullen and Marsden, 2016). Lucas et al., have attempted to unify a definition of transport poverty, incorporating factors such as accessibility and exclusion (Lucas et al., 2016). It is worth noting that "sub-terms" raised in this paper such as "forced car ownership" rarely arise in a literature search on Web of Science unless the term itself is used, or a search term so wide as to be meaningless and would require many hours of manual filtering is used. Thus, this review has searched for specific terms in the transport poverty literature, but we acknowledge that there may be items this review has missed. To counter this, we have added grey literature where necessary.

This review has adopted a systematic approach as outlined by Tranfield et al., which is appropriate due to the evidence base for the following four reasons:

1. Quantitative and qualitative studies are used in the literature, and positivist and interpretivist approaches can thus be incorporated
2. The literature in fuel and transport poverty has evolved considerably over their respective lifespans, with little consensus over what should be measured and how
3. Experimental research design is not utilised, and possibly infeasible – data is usually collected via surveys of either opinions or behaviours
4. Many factors in the literature are in a state of continuous flux (e.g. household budgets, fuel and energy prices, etc).

This systematic review aims to both enhance the knowledge basis in the fields of study and inform policymaking and practice (Tranfield et al., 2003). The research process we have followed, starting with literature collection is shown in Fig. 2.

3.1. Literature gathering

A bibliometric analysis was first conducted to assess as complete a picture of the literature as possible. Bibliometric analysis is a statistical evaluation of articles that seeks to determine the influence of publication on the literature and the wider world (Iftikhar et al., 2019). This phase aimed to be as wide as possible within the fields of energy and transport whilst excluding extraneous literature. To this end, a list of search terms was developed, some of which were "sub-terms" as described in Section 3. The following paragraphs describe the search terms used on the Web of Science (WOS) platforms on 15/05/2020 to find literature for this review.

For fuel poverty:

$$(\text{TS} = (\text{“Fuel poverty”OR“Energy poverty”}) \text{ AND Language} \\ : (\text{English}) \text{ and Document Types} : (\text{Article})$$

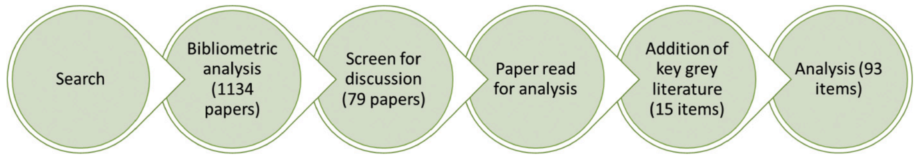

Fig. 2. Development of literature Corpus for analysis.

Indexes = All

Timespan = 1970–2020,

For transport poverty:

(TS = ("transport poverty"OR"mobility poverty"OR"accessibility poverty"OR"transport affordability"OR"transport deprivation"or"forced car ownership")

and Language : (English) and Document Types : (Article)

Indexes = All

Timespan = 1970–2020,

where TS is the topic field assigned by the WOS.

The Corpus of literature yielded was uploaded to the CorTexT Manager where it was analysed (Laboratoire Interdisciplinaire Sciences Innovations Sociétés, 2020). For a description of the methods the CorTexT Manager uses, see Marvuglia et al. (2020). The following aspects of the metadata from the corpus were analysed:

- Paper authors,
- Country of author origin,
- The journals in which the literature was published,
- The volume of publications through time and the relation to external factors,
- Contingency matrices, which show the co-occurrence of terms and journal names,
- The networks of keywords in each literature.

The following limitations apply to the data gathered via these searches and the subsequent analysis:

- Due to the 'articles only' search term used in WOS, some key literature lies outside the search terms (e.g. key Government reports such as the Hills Report), which were added later. Therefore at this stage excluded documents types include: books and book chapters, news articles and commentary, and workshop write-ups,
- Only English language documents are analysed,
- Only one search engine was used due to the need to format data for analysis,
- The results present a snapshot in time of the literature, and items published after the search date of 15/05/2020 are not included in this analysis. This is a necessary consequence of the need to have static data on which to conduct the bibliometric analysis,
- Human error is possible during the analysis process.

Table 1
Literature exclusion criteria.

Exclusion criteria	Stage: Screen by title	Stage: Screen by abstract
Topic	Exclude studies not explicitly concerned with energy or transport poverty	Exclude studies not explicitly concerned with energy or transport poverty
Study design	No restrictions	Exclude studies not focused on the measurement or application of measurement, analysis of or subjective experience of energy and transport poverty

The criteria applied during the screening stage (between data collection and analysis) were multiple and are summarised in Table 1 below.

Firstly, papers were screened by title to exclude studies which were obviously outside the scope of this research, for example, studies concerned with sustainability assessments of technologies. At this stage, no exclusionary criteria were applied to the study design. In the second phase, papers were excluded based on the contents of their abstracts. As for topics, studies that considered areas outside energy or transport poverty were excluded, as was the case during the screen by title phase. With regards to study design, we analysed research concerned with metrics in energy and transport poverty themselves or research which applied those metrics to case studies. We additionally considered research concerned with the risk of or vulnerability to energy and transport poverty, as well as research concerned with subjective experiences.

We do not believe that any one search alone can be considered truly comprehensive. Nevertheless, in order to counter these limitations, some key grey literature was added. Additionally, many of these debates occur in the policy literature requiring us to search the grey literature. Lastly, it is worth reading the grey literature to determine if findings from academic literature are making an impact outside the academy.

4. Results: author, journal, and publication trends within the literature

We have analysed which authors are most frequently cited in these fields. The reasons for this are multiple. Firstly to determine how many researchers have deep expertise in this area and as a consequence of this, then secondly, whether this field is of deep concern to a small group of researchers or a multitude. Thirdly to understand which institutions play a key role in debates in this field and fourthly to understand which lens these researchers view these debates with.

4.1. Analysis of authors

The top 20 authors by frequency of publication for the search ("Fuel

Table 2
Top 20 Authors in fuel and energy poverty.

Author	No. of records	Institution (Current)	University ranking 2020 (QS)	Country	Discipline[a]
Sovacool BK	31	University of Sussex	246	England	Energy Policy
Bouzarovski S	20	University of Manchester	27	England	Geography
Urpelainen J	15	Johns Hopkins University	24	USA	Energy, Resources and Environment
Thomson H	11	University of Birmingham	81	England	Global Social Policy and Sociology
Petrova S	10	University of Manchester	27	England	Geography
Liddell C	9	Ulster University	601–650	Northern Ireland	Psychology
Pachauri S	9	International Institute for Applied Systems Analysis	N/A	Austria	Transitions to New Technologies
Santamouris M	9	University of New South Wales	43	Australia	High Performance Architecture
Day R	8	University of Birmingham	81	England	Environment and Society
Galvin R	8	University of Cambridge	7	England	Environmental Science
McCauley D	8	Erasmus University Rotterdam	183	The Netherlands	Management of International Social Challenges
Rubio-Bellido C	8	University of Seville	601–650	Spain	Architecture and Environment
Snell C	8	University of York	148	England	Social Policy
Bazilian M	7	Colorado School of Mines	N/A	USA	Public Policy
Gilbertson J	7	Sheffield Hallam University	801–1000	England	Regional Economic and Social Research
Gouveia JP	7	NOVA University Lisbon	421	Portugal	Environmental Sciences and Engineering
Herrero ST	7	University of Manchester	27	England	Environment, Education and Development
Howden-Chapman P	7	University of Otago	176	New Zealand	Public Health
Smart S	7	University of Queensland	47	Australia	Chemical Engineering
Walker G	7	Lancaster University	128	England	Environment
Others	2778	Various	N/A	Various	N/A

[a] As listed on Author webpage on their respective University websites.

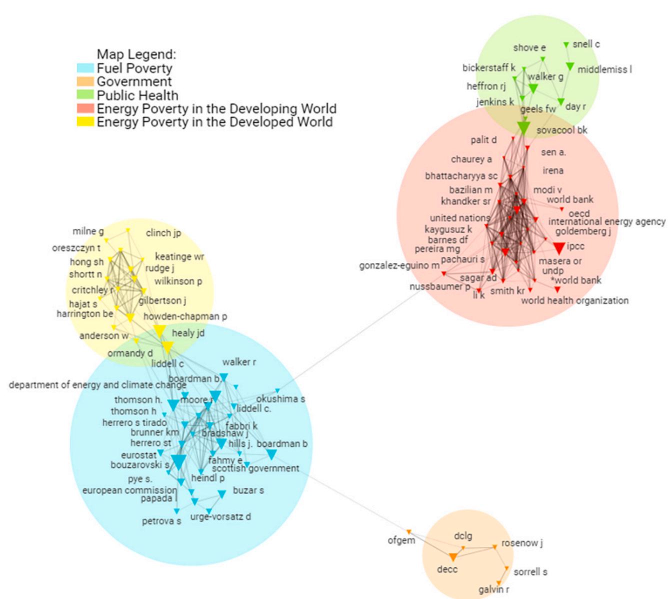

Fig. 3. Network of authors in fuel and energy poverty.

Poverty") and ("Energy Poverty"), which resulted in 984 total papers are shown in Table 2. Note that the number of records is specific to each author, and authors will frequently appear on the same paper together. This table details the top 20 authors, representing less than 1% of total number of authors publishing in this corpus. A very long tail of authors publishing a few or single studies is present in the literature, with over 2,000 other authors present in the corpus.

Fig. 3 shows the networks of authors in the fuel and energy poverty corpus. The top 100 authors are displayed, with the lines connecting these authors representing co-occurrences of the author names. We see here multiple groups or clusters forming, specifically: researchers in "fuel poverty"; researchers in "energy poverty in the developing world"; researchers in "energy poverty in the developed world"; researchers in "public health"; and researchers in "government". Thus, we can see that research is prominent in areas concerning equity. There are small overlaps and some links between the clusters, but we can see that they are more strongly distinct than they are united. In other words, researchers within each cluster tend to work within their cluster subject, and work with other authors from that cluster. Indeed, inter-cluster work is rare, as we can see in the (until recently distinct) research in fuel and energy poverty, which are slowly coalescing in the developed world. To some extent, this can be explained by the separate geographies of study, and also, by the separate problem definitions each group has chosen. Therefore, we can say that there is yet work to be done to unite these groups and research fields.

Table 3 highlights are the top 12 authors by frequency of publication in transport poverty; the search yielded 150 total papers. Note that the number of records is specific to each author in the table below, and authors will frequently appear on the same paper together. This table detailing the top 12 authors representing approximately 4% of total number of authors publishing in this corpus. Again, a long tail of authors publishing a few or single studies is present in the corpus, with nearly 300 other authors present.

Fig. 4 shows the networks of authors in the transport poverty corpus. The top 100 authors are displayed, with the lines connecting these authors representing co-occurrences of the author names. The corpus of transport poverty literature is much smaller than that of fuel and energy poverty, numbering 150 papers, and this literature is much more nebulous than the fuel poverty corpus and is scattered across a large number of search terms. A cluster can be seen for researchers in topics of specifically: "transport poverty"; "transport justice"; "transport planning"; "transport engineering"; and "public transport". We can see here that areas of research are more explicitly concerned with equity than research in fuel and energy poverty. This corpus is somewhat more

Table 3
Top 12 authors in transport poverty.

Author	No. of records	Institution (Current)	University ranking 2020 (QS)	Country	Discipline
Lucas K	12	University of Leeds	93	England	Transport and Social Analysis
Currie G	8	Monash University	58	Australia	Transport Engineering
Hine J	7	Ulster University	601–650	Northern Ireland	Transport Planning
Mattioli G	7	Technische Universität Dortmund	751–800	Germany	Transport Planning
Delbosc A	6	Monash University	58	Australia	Transport Engineering
Farber S	5	University of Toronto	29	Canada	Transportation Geography and Spatial Analysis
Kamruzzaman M	5	Monash University	58	Australia	Urban Planning
Cullen P	4	University of New South Wales	43	Australia	Public Health
Fransen K	4	Vrije Universiteit Brussel	195	Belgium	Geography
Hunter K	4	University of New South Wales	43	Australia	Global Health
Ivers R	4	University of New South Wales	43	Australia	Public Health
Stanley J	4	Monash University	58	Australia	Urban Social Resilience
Other	318	N/A	N/A	Various	N/A

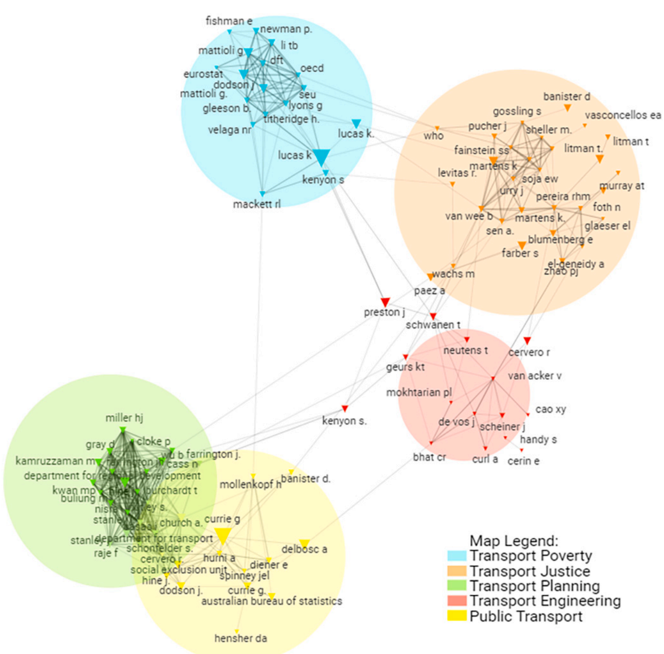

Fig. 4. Author networks in transport poverty.

Table 4
Top 20 Journals (publications per Journal) in fuel and energy poverty.

Source title	No. of records
Energy Policy	180
Energy Research & Social Science	82
Energy and Buildings	67
Energy for Sustainable Development	25
Energies	22
Sustainability	21
Applied Energy	20
Energy	19
Indoor and Built Environment	14
Renewable Energy	12
Journal of Cleaner Production	11
Energy Efficiency	10
Building Research and Information	9
Energy Economics	9
Energy Sources Part B Economics Planning and Policy	9
International Journal of Environmental Research And Public Health	9
Renewable Sustainable Energy Reviews	9
Sustainable Cities And Society	9
Environment and Planning A, Economy And Space	8
Journal of Energy In Southern Africa	8
Other	611

biased than the fuel/energy poverty corpus due to the rather specific search terms that had to be known to yield some results instead of the other corpus, which is based on only two terms. A self-fulfilling cycle seems to appear in this corpus in that the research is itself interdisciplinary, but in the sense that it combines many disciplines into one small area, rather than cross the boundaries of many disciplines, and thus each literature cluster does not seem to move beyond its own "silo".

4.2. Journals

Next, in Table 4, we have analysed in which journals research in energy and transport poverty is most frequently published. From this, we can see how the debate in these fields is framed and for which audience these debates are aimed at.

From Table 4, we can see that common themes are policy, social science, development and buildings. There is a long tail of journal papers in the “Other” category that appear in journals with fewer than 8 publications in this field. We can see that there is less focus in the literature on e.g. economics; it appears from this list that despite attempts to use quantitative metrics, fuel poverty is rarely studied in the disciplines which consider themselves quantitative. Furthermore, if fuel poverty has rarely been considered by energy economists, can we be confident that the policy research is actually effecting change in economic practice? At first glance, this casts doubt on whether or not economists are capturing the appropriate return on investment on fixing fuel poverty; or indeed if economists are truly considering the likes of mental health and educational benefits. If we are not correctly measuring improvements to equity, can we be sure that we value them? Additionally, it can be noted that at first glance, this does not seem to be a problem much studied by engineers, who consider it their field to provide technical solutions to problems. How might they seek to alleviate energy poverty?

Table 5
Journals with more than one publication in transport poverty.

Source title	No. of records
Journal of Transport Geography	31
Transport Policy	16
Transportation Research Part A Policy And Practice	11
Journal of Transport Health	5
Transport Reviews	5
Research in Transportation Economics	4
Social Inclusion	4
Transportation Research Record	4
Cities	3
European Transport Research Review	3
Transportation	3
Research in Transportation Business and Management	2
Transfers Interdisciplinary Journal Of Mobility Studies	2
Travel Behaviour And Society	2
Voprosy Istorii	2
Other	53

As shown in Table 5 the majority of transport poverty research is in the disciplines of geography and policy. This is rarely crossing over into other journals such as *Cities* so we might say that this "interdisciplinary" area of study is not crossing disciplines or being read outside its own sphere. Here, again, we reiterate our point that, as with energy poverty, at first glance, there does not seem to be much focus on technical solutions to these issues.

4.3. Publications and exogenous trends

Figures 5, 6, 7 and 8 show the number of publications in each discipline through time versus some UK exogenous trend data. The reason for choosing UK data is that the fuel/energy poverty literature is dominated by UK studies, more than twice the number of the second-most studied country, the USA, and is the second most studied country in the transport poverty literature behind Australia. Using UK data across both fields allows for consistent comparisons. Note that the trendlines illustrated on each graph are lines of best fit through the existing data and not statistical inferences of correlation between the two data sets displayed together. We do not wish to draw spurious conclusions from our analysis of these data. Indeed, we believe that this ought to be an area of further research.

Furthermore, we are examining the full corpus rather than the refined list of studies in these charts: this serves the purpose of identifying "interest" in terms of publication frequency without biasing the results with the studies we deem to be most impactful in these fields. For brevity, in this sub-section when we use the term energy poverty to describe a body of literature, we are also including fuel poverty in this body.

Of note in Fig. 5 is that in energy and fuel poverty, we are now seeing approximately 200 publications per year. We suggest that to keep track of this growing body of literature, increased use of team research or computer assisted methods may be necessary. As shown in Fig. 5, there is a visible trend in both, increasing numbers of publications and domestic energy (electricity) prices (Ofgem, 2020).

As with energy poverty publications and domestic energy prices, Fig. 6, shows there is a broadly consistent increasing trend between transport poverty publications and motor fuel prices (Department for Business, Energy and Industrial Strategy, 2020). Indeed, the peaks and troughs in prices and articles published per year roughly coincide, though we do not draw conclusions from this. Note the same increasing trend is visible with diesel prices, though only petrol prices have been visualised for ease of viewing.

Fig. 7 shows UK real gross weekly earnings versus publications in fuel and energy poverty through to May 2020. Wages, whilst on a long-term upward trend, have been broadly stagnant since the Great Financial Crisis whilst interest in fuel and energy poverty has increased, alongside the background of increasing energy prices. Of note also is that the number of publications in energy poverty declined during the period of the Great Financial Crisis; the reason for this is unclear.

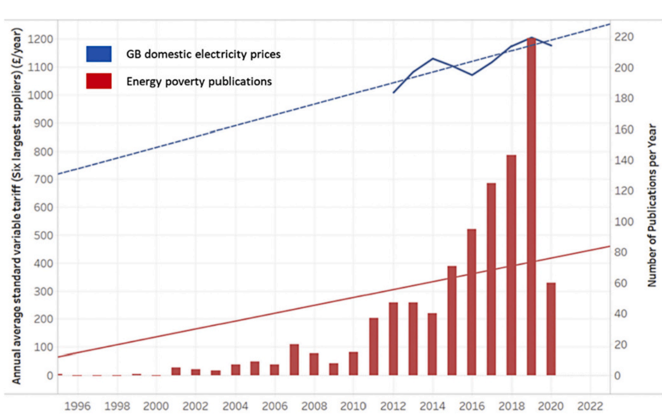

Fig. 5. Showing Great Britain annual average standard variable tariffs, energy poverty publications, and their trends through time.

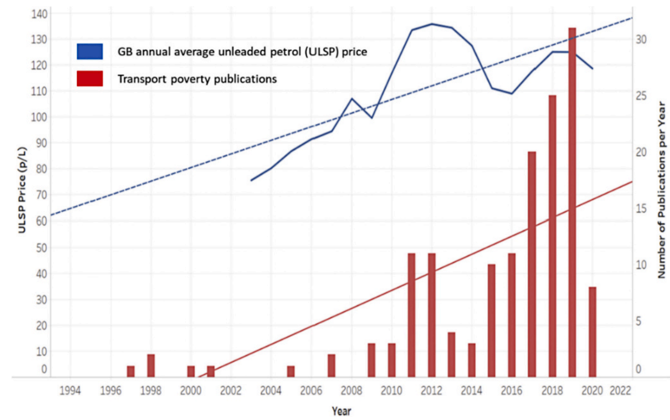

Fig. 6. Showing Great Britain annual average petrol prices, transport poverty publications, and their trends through time.

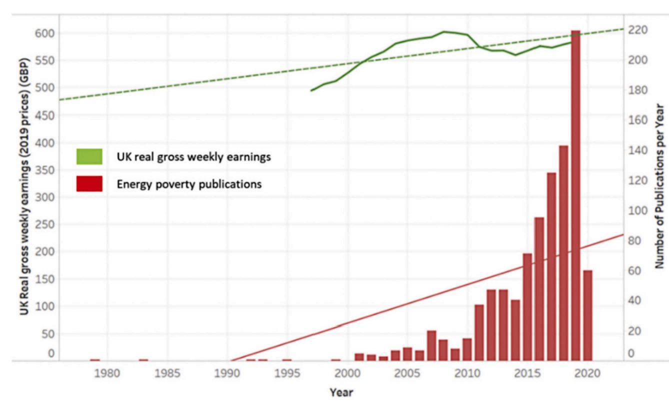

Fig. 7. Showing United Kingdom real gross weekly earnings, energy poverty publications, and their trends through time.

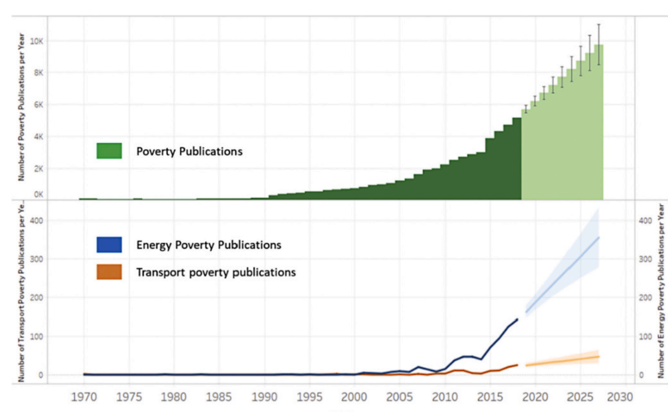

Fig. 8. Showing the number of publications per year in poverty, energy poverty and transport poverty, and their forecasts.

Fig. 8 shows the number of publications per year in poverty, energy poverty, and transport poverty to 2018, and forecasts their future publication volumes using the existing trends (Tableau, 2020). Energy poverty publications are expected to roughly treble in volume by 2027, with poverty publications roughly doubling over this time period. Transport poverty publications are also expected to roughly double by

2027, but this will still only achieve the low volume of approximately 50 per year. Given these trends it might be said that whilst interest remains highest in poverty, energy poverty is the fastest growing area of study.

4.4. Where do salient terms appear?

The following contingency matrices show the correlation between objects A_i and B_j. In this instance, we show the top 10 most frequently co-occurring terms in the literature and the journals in which they appear. Thus, these graphs are useful for depicting which terms the research field cares most about, and in which journals researchers interested in these terms publish. The colour scheme shows the frequency of a given term in a given journal vs the expected frequency of this term in that journal using the χ^2 test as the measure of statistical correlation. If negative, (e.g. a value of -2), this means that the co-occurrence of these terms is 200% lower than the expected number of co-occurrences. Additionally, a Fisher test was conducted in order to determine if the deviation has a *p*-value exceeding 0.05 i.e. if the deviation has a significance above 5%. In these cases, the cells are marked with an X, meaning that we cannot reject the null hypothesis, (where the null hypothesis means that the increase for positive values in the matrix and the decrease of negative values in the matrix is not the result of a causal relationship between A_i and B_j).

From Fig. 9, we can see the concept of justice appearing frequently in the *Applied Energy* and *Energy Research & Social Science* journals. Either this is a result of pre-selection of journals by authors; or alternatively, the editors of these journals disproportionately favour these topics over others. Furthermore, we can see concerns run high regarding a just transition in the fuel poverty social science research. Consequently, equity is an area of deep interest in the literature.

As perhaps expected, we see "energy access" frequently occurring in *Energy & Sustainable Development* and we see "renewable energy" appearing often in *Renewable Energy*. In short, as we have seen with Table 4 fuel and energy poverty are studied primarily by social scientists. Indeed, it was clear from the analysis that discipline silos have not been broken down, and these areas of study have not fully translated to the engineering disciplines, which also bear responsibility for these issues.

From Fig. 10 we can see that "transport justice", "wellbeing" and "transport poverty" have highest occurrence above expected.

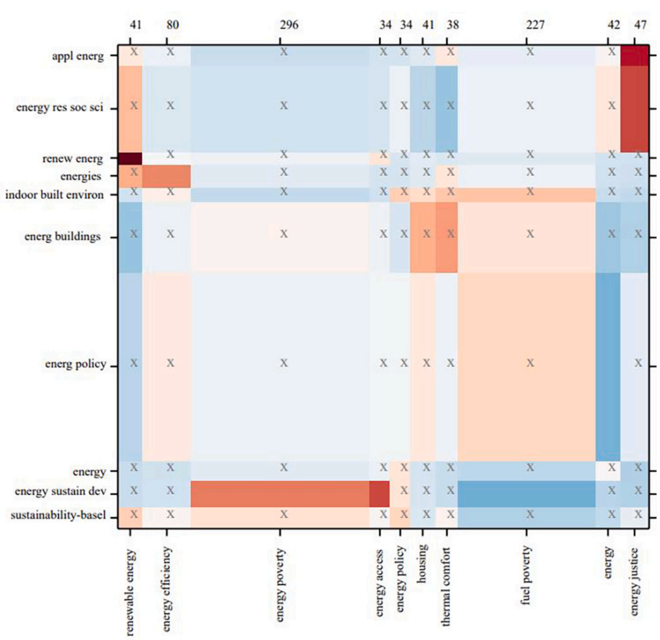

Fig. 9. Showing the contingency matrix for the energy poverty literature.

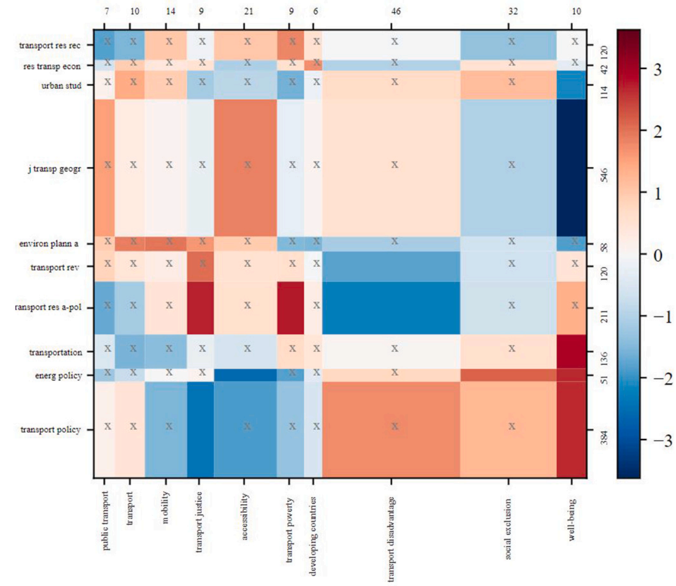

Fig. 10. Showing the contingency matrix for the transport poverty literature.

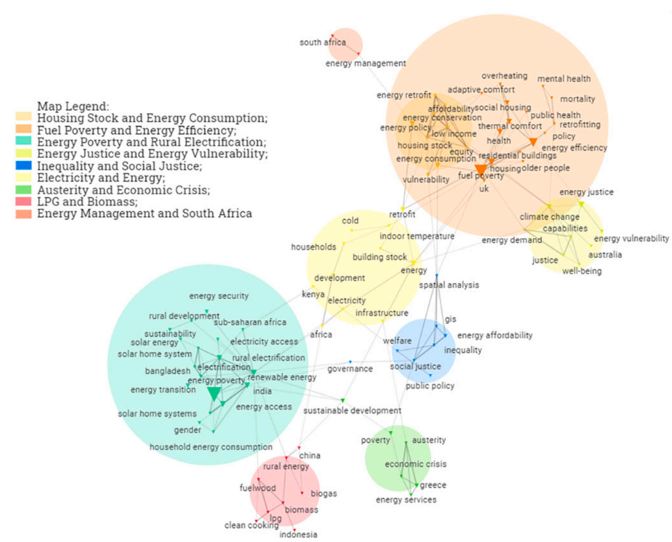

Fig. 11. Showing the network of keywords in energy poverty.

"Accessibility" is the largest concern in the most popular journal, the *Journal of Transportation Geography*. *Energy Policy* features in this contingency matrix showing that transport poverty has crossed into the energy field, but the reverse does not hold as fuel poverty has not greatly crossed over into the transport poverty field. In conclusion, we can say that as with fuel and energy poverty, transport poverty is most commonly studied by social scientists.

4.5. Which networks form around keywords?

From Fig. 11 we can see keyword clusters forming around the following topics: "housing stock and energy consumption"; "fuel poverty and energy efficiency"; "energy poverty and rural electrification"; "energy justice and energy vulnerability"; "inequality and social justice"; "electricity and energy"; "austerity and economic crisis"; "LPG and biomass"; "energy management and South Africa".

These clusters emerge for many reasons, but not least because the vocabulary of each issue is limited. That is to say that people who do not

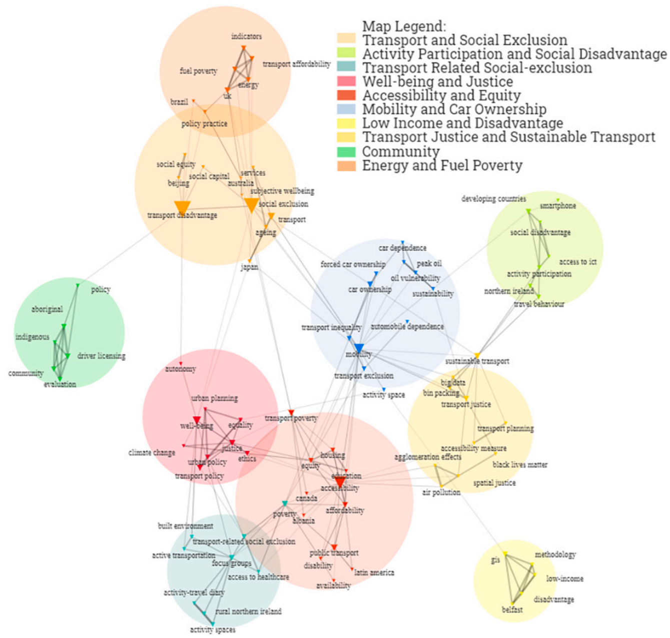

Fig. 12. Showing the network of keywords in transport poverty.

know the precise terms or details of a given topic may miss core parts of the field they are searching, or that the terms of art in each field are prerequisite knowledge, and thus we expect that this poses a barrier for translating research from the academy into the policy world.

From Fig. 12 we can see keyword clusters forming around the following topics: "transport and social exclusion"; "activity participation and social disadvantage"; "transport related social-exclusion"; "well-being and justice"; "accessibility and equity"; "mobility and car ownership"; "low income and disadvantage"; "transport justice and sustainable transport"; "community"; and "energy and fuel poverty". Again, it is difficult for transport poverty to cross disciplines whilst continuing to use the same language it always has. It is noteworthy that energy and fuel poverty appear in this keyword network. This is likely due to some methodology overlap, as we later note.

4.6. Evolution of keywords through time

From Fig. 13, in early research, we can see the stark fuel poverty-energy poverty binary; "energy poverty & rural electrification" and "housing & fuel poverty." The research has become more fragmented through time; early interest was dominated by two main search terms, whilst we now see newer interest from 2015 onwards in items such as "indicators and fuel poverty", and more recently "energy justice", i.e. in early research, academic interest was focused on a small set of topics, which in recent times has broadened into a larger number. This reflects the uncovering of novel issues as the research has evolved and changing wider interests and contexts (e.g. the appearance of "austerity" and its impact on the research field).

From Fig. 14 we can see in early transport poverty research that many disparate terms appear. Moving towards the present day, we see a lack of consolidation, and again the emergence of justice and equity concerns. It would appear that not only is transport poverty research rather nebulous, but new issues e.g. "big data and data visualisation" are uncovered over time without any single issue dominating the work. Furthermore, there are fewer connections between early key terms and key terms from 2015 onwards in transport poverty when compared with energy poverty. Indeed this is not surprising when we examine the inherently nebulous definition of transport poverty as proposed by Lucas et al. in the subsequent section (Lucas et al., 2016).

5. Conceptualizing and critiquing energy and transport poverty metrics

The literature analysed in the following section includes the addition of key grey literature required to paint a fuller picture of what is state of the art in energy and transport poverty metrics.

5.1. Contributors and drivers of energy and transport poverty

The definition of fuel poverty has evolved through time, and at

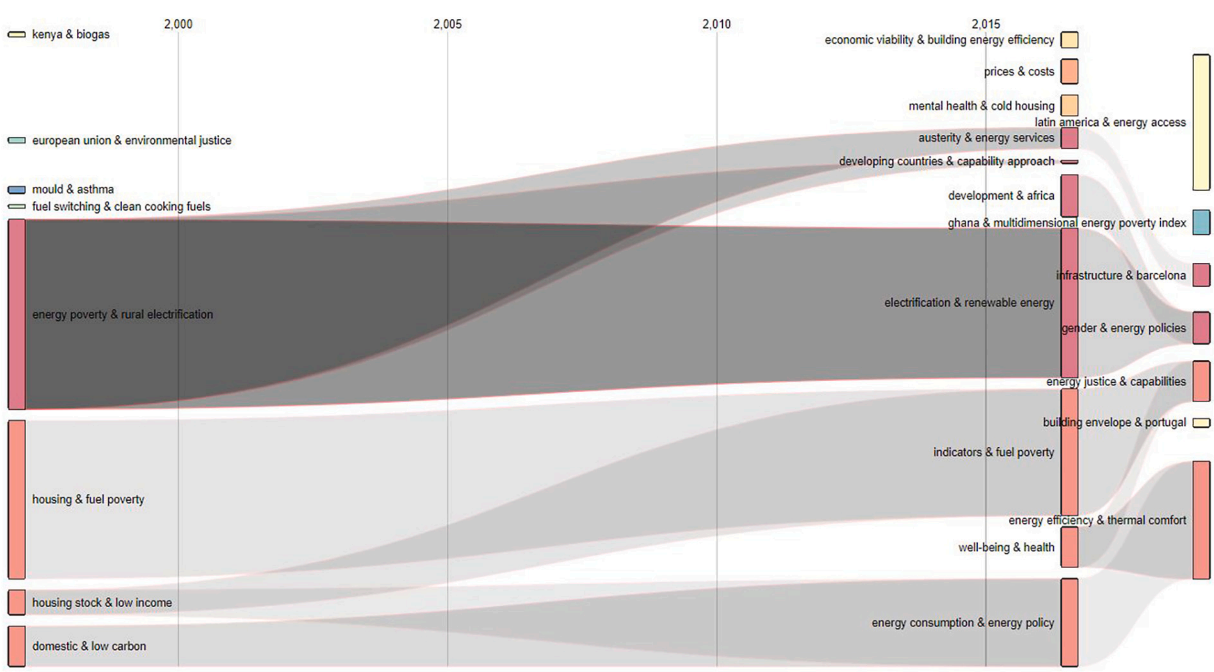

Fig. 13. Showing the evolution of keywords in energy poverty through time.

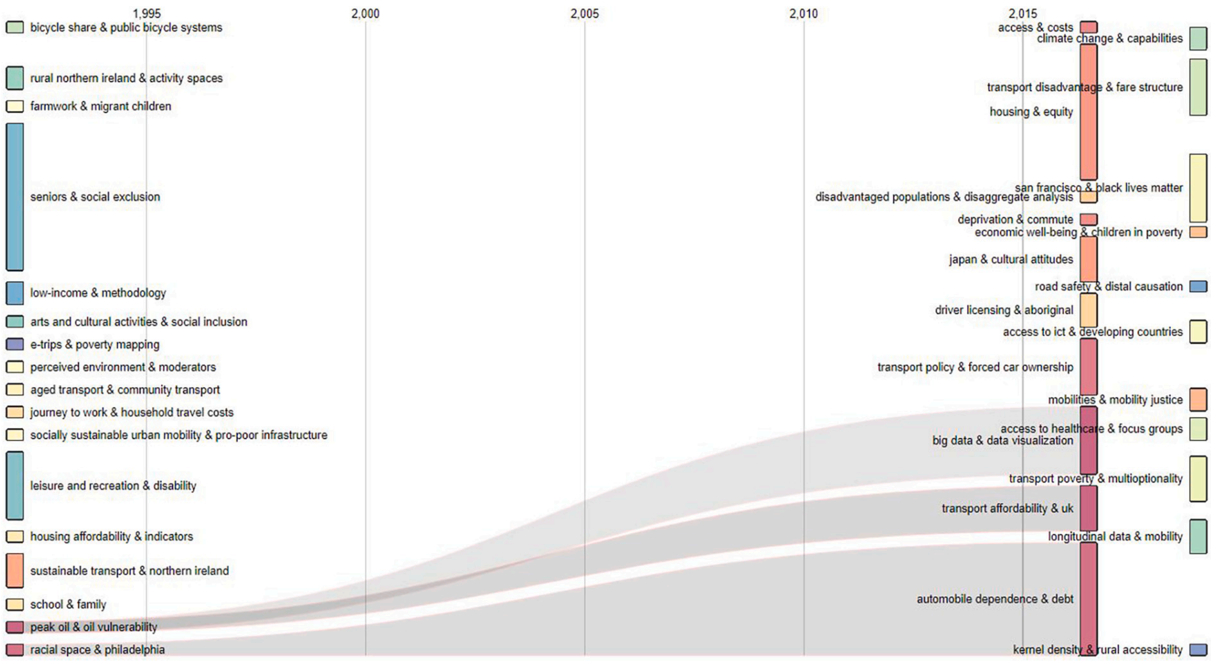

Fig. 14. Showing the evolution of keywords in transport poverty through time.

present, typically cover full household energy use rather than just heating. For example, Liddell et al., borrowing from the Institute of Engineering and Technology recognise the following contributions:

1. "*The income of the household,*
2. *The cost of fuel and ease or otherwise of fuel substitution,*
3. *The efficacy of the heating system, and the ability to do anything about it,*
4. *The energy efficiency of the building fabric, and the ability to do anything about it,*
5. *Under-occupancy (a particular problem leading to fuel poverty in the elderly),*
6. *The ability of the householders to use energy efficiently,*
7. *The attitude to energy use (though the fuel poor are often acutely (and dangerously) aware of the energy they use),*
8. *The ability of the customer to respond to price and other signals,*
9. *The ability to adopt new technologies.*"

(Liddell et al., 2011) (Institute of Engineering and Technology, 2010). Implicit within these contributions are concerns regarding equity. For example, the ability of a household to use energy efficiently is a function of the efficiency of household's appliances, which can, in turn, depend on the household's income.

Bouzarovski and Petrova apply a lens of vulnerability factors to derive the following aspects of energy poverty, in summary:

1. Access – poor availability of energy carriers,
2. Affordability – high disparity between fuel cost and income,
3. Flexibility – (in)ability to change form of energy provision,
4. Energy efficiency – disproportionately high fuel use for energy provided,
5. Needs – mismatch between household energy requirement and energy available,
6. Practices – lack of knowledge or political recognition of support, and lack of knowledge on how to use energy efficiently.

This uncovers many of the same factors as the aforementioned earlier work, but from a different perspective, e.g. where "attitudes to energy use" can be seen to overlap with "practices" (Bouzarovski and Petrova, 2015). These factors are also implicitly concerned with equity issues, such as access and availability of different energy carriers.

So how do we capture these factors in a metric? Clearly, some of these are not directly quantifiable, such as the *ability* to use energy efficiently. Actual and expected energy usage can be modelled, or elasticity functions can be created to simulate behaviour, but these measures are proxies only.

The study of transport poverty as it would be recognised today has come through the coalescing of previously disparate research. The earliest mention this review has found dates from 1973, where this initial consideration of transport was in terms of social and economic inequality (Wachs and Kumagi, 1973). Other key early proponents come from the grey literature. The GCCNI first considered "transport poverty" to be a condition brought on by a combination of the following: restricted choice of transport; government neglect of public transport; high transport costs; and unsatisfactory quality of public transport services. The report then highlighted the disadvantages associated with and caused by transport poverty (General Consumer Council of Northern Ireland, 2001).

Later the Social Exclusion Unit (SEU) identified five key transport barriers: 1) availability and physical accessibility of transport, both public and private; 2) the cost of personal and public transport; 3) the inaccessible locations of services or other desirable locations; 4) safety and security of transport modes, (e.g. the safety of public transport at night); and lastly 5) travel horizons, (i.e. a person's willingness to travel long distances). In turn, multiple causal factors were listed: a historical lack of taking responsibility for ensuring that transport routes led to key services and employment; before 2000, the social costs of poor transport were not really considered in project appraisal; public spending on public transport has been fragmented, i.e. resources have not been joined up in order to improve accessibility; the deregulation of bus fares in the 1980s led to an increase in fares; land use planning policies in the 1980s and 1990s encouraged land use patterns that favoured those with access to a car (e.g. out of town shopping centres); and the holding back of solutions, in some cases due to incompatible legislation (Social Exclusion Unit, 2003).

From SEU's insights, we can see the emergence of future literature themes, in some cases without them being explicitly named, such as affordability; forced car ownership; activity space; adequate service; and car related economic stress. In 2012 the Royal Automobile Club, RAC

Foundation explicitly acknowledged the analogy of fuel poverty and adopted the 10% metric for transport poverty, finding (at the time) that four fifths of British households were in transport poverty (RAC Foundation, 2012).

Lucas noted, in 2012, that significant progress had been made on the volume of research in transport and social exclusion, on the methods used in this research, and that validity had been added to the claim that transport related social exclusion can stand as a distinct concept (Lucas, 2012). Yet, even at this stage, the need to establish metrics was noted as an ongoing need. Lucas et al. would later examine what transport poverty is comprised of and its explicit distinctions from poverty by itself (Lucas et al., 2016), describing transport poverty as encompassing transport poverty itself, transport affordability, mobility poverty, and accessibility poverty.

Additionally, exposure to transport externalities (e.g. air pollution), also warrants consideration. Lucas et al. have elaborated on this definition saying "*An individual is transport poor if, in order to satisfy their daily basic activity needs, at least one of the following conditions apply: 1) there is no transport option available that is suited to the individual's physical condition and capabilities; 2) The existing transport options do not reach destinations where the individual can fulfil his/her daily activity needs, in order to maintain a reasonable quality of life; 3) the necessary weekly amount spent on transport leaves the household with a residual income below the official poverty line; 4) the individual needs to spend an excessive amount of time travelling, leading to time poverty or social isolation; 5) the prevailing travel conditions are dangerous, unsafe or unhealthy for the individual*" (Lucas et al., 2016).

5.2. Key metrics

5.2.1. Energy poverty metrics

Energy poverty metrics typically follow three approaches (Thomson et al., 2017a) and will be discussed in this order:

1. Expenditure measures which examine energy expenditure against a threshold,
2. Consensual, or self-reported measures, where households respond to surveys,
3. Direct measurement, which compares measured home energy use against standards.

The history of metrics from that time will be discussed below, starting with expenditure measures and then discussing consensual measures. Notably, direct measurement is not used in the most widely cited literature, which we attribute to the difficulty of collecting such data from households.

Boardman's book of 1991 defined fuel poverty to mean "*the inability to afford adequate warmth because of the inefficiency of the home*" and set a threshold for being considered fuel poor to cover households whose fuel expenditure on exceeded 10% of their income (Boardman, 1991). This was the first expenditure measure and was what the poorest 30% of households were then spending on fuel, and at twice the median expenditure, was a threshold above which spending was considered 'disproportionate'. The temperature requirement as chosen by Boardman was set out by the World Health Organisation (WHO) (World Health Organisation, 1985).

In 2012, Moore proposed the use of minimum income standards (MIS) to measure fuel poverty (Moore, 2012). Minimum income standards are a social science tool defining the minimum income required for a household to have a certain standard of living. Households are classified as fuel poor if, after deducting their actual housing costs, they have insufficient residual net income to meet their total required fuel costs (as measured by the English Housing Survey (EHS)) after all other minimum living costs (as defined by the MIS) have been met. That is to say a household is in fuel poverty if (fuel costs > net household income – housing costs – minimum living costs). Moore considered this budget standard approach to be a fairer and more meaningful indicator for comparison across households.

The largest shift in fuel poverty metrics in the UK occurred in 2012 with the advent of the Hills Report (Hills, 2012, p. 9). Now households were considered fuel poor if they have: "*1) required fuel costs greater than the median; 2) if they spend that much on fuel they would be left with a residual income below the official poverty line*". The report advocates that the indicator clearly highlights the benefits of energy efficiency improvements for low income households.

The Scottish Fuel Poverty Act 2019 (Scottish Parliament, 2019, p. 2) stated a household is in fuel poverty if "*(a) the fuel costs necessary for the home in which members of the household live to meet the conditions set out in* Section 2 *i.e. the heating regime are more than 10% of the household's adjusted net income, and (b) after deducting such fuel costs, benefits received for a care need or disability (if any) and the household's childcare costs (if any), the household's remaining adjusted net income is insufficient to maintain an acceptable standard of living for members of the household*". Thus, this definition combined both an expenditure threshold based on the Boardman definition and adapted the MIS concept.

Healy and Clinch developed an early set of consensual measures to measure fuel poverty across the European Union (EU) due to a lack of consistent member state wide data: "*the ability to pay to keep the home adequately warm, arrears on utility bills, and the presence of a leaking roof, damp walls or rotten windows*" (Healy and Clinch, 2002). The advantage of these metrics is that they can be applied to any household regardless of national circumstance and thus, allow for comparison across countries. Furthermore, this study appears to be the first major new contribution to the literature to consider more than just the household heating regime i.e. the first to consider "energy" poverty as we now understand it.

The European Commission (EC) has developed consensual indicators of energy poverty (in their lexicon) based on the Statistics on Income and Living Conditions (SILC) survey. This survey is up to each of EU27 to undertake, and as such, wording varies, but common question topics include: ability to keep the house warm; arrears on utility bills; if spending on utility bills limits other expenditure (European Commission, 2020). The expenditure based metrics are summarised in Table 6.

In Table 7 we list a host of variations of the measures discussed in order to illustrate the multitude of adaptations authors have taken in attempts to overcome metric limitations or to adapt to specific circumstances.

5.2.2. Transport poverty metrics

As stated in the introduction, we define transport poverty in this review as the enforced lack of mobility services necessary for participation in society, resulting from the inaccessibility, unaffordability, or unavailability of transport.

In the UK, the RAC Foundation notes that in 2018–19 the poorest decile of households spent a quarter of their income on car-related expenses (RAC Foundation, 2020). Other aspects of transport poverty are rarely studied in Government or NGO literature. Each of transport poverty, affordability, mobility poverty, and accessibility poverty, in turn, have different descriptive measures seeking to capture them. As transport poverty is considered to be an overarching condition caused by one of the other factors, research quantifying "transport poverty" in the literature has been categorised into the appropriate subset. This is in line with recommendations from Lucas' earlier work to form a common lexicon for transport poverty (Lucas and Markovitch, 2011).

Of note, is that the unit of measurement is not the same as that of fuel poverty; individuals rather than households experience transport poverty (of course, this may mean all of the individuals within a household are transport poor). Furthermore, housing costs should also be considered in a transport poverty metric as an individual may trade-off between housing and transport costs i.e. an individual may live in a more expensive property to save on transport costs (Lucas et al., 2016). Much of the research in these disciplines is not focused on measuring

Table 6
Listing expenditure based energy/fuel poverty metrics.

Source	Metric/ Method	Warmth or all household energy?	How does this deal with income?	How does this deal with expenditure?	How does this deal with heating regime?
Boardman (1991)	10%	Energy - space heating, water heating, lights, appliances and cooking	Income of the whole household, with council tax deducted, but not water bills.	Required spending: 10% of income spent on heating i.e. twice median expenditure, which poorest 30% of households spent. This expenditure was considered “disproportionate” but is essentially arbitrary. The metric measures “need to spend”, thus accounting for those who cannot afford to spend this much.	21 °C in living room and 18 °C in other rooms for 9 hours each weekday, and 16 hours a day at weekends. This assumes a single climatic regime but is adjusted in terms of heating regime for the elderly and disabled allowing for 23 °C in living room for 16 hours a day for every day. Adjustments are also made for underoccupancy.
Hills (2012)	Low Income High Cost (LIHC)	Energy - space heating, water heating, lights, appliances and cooking	Median household income from the EHS. No adjustments for any other expenditure such as council tax.	A household must have required fuel costs that are above the national median average, and if they spent that amount, they would be left with a residual income below the official poverty line. No other household expenditure is considered	Heating regime and median energy costs as defined and reported by the EHS. No adjustments for the elderly, disabled, or under-occupancy.
Moore (2012)	Minimum Income Standard (MIS)	Energy – requirements as set out in EHS	Council Tax, rent and mortgage payments (from the EHS) are deducted from household income	Once actual housing costs, and all other minimum living costs (as defined by the MIS) are deducted a house is in fuel poverty if they have insufficient residual net income to meet their total required fuel costs.	Total required fuel costs as measured by the EHS.
Scottish Parliament (2019)	Scottish Fuel Poverty	Legislation states heating regime, not all energy expenditure.	Household income adjusted to account for (a) rent, (b) council tax and water rates,(c) fuel, (d) childcare.	To be fuel poor a household must spend more than 10% of its adjusted income on fuel and the remainder of its adjusted income (deducting benefits for care needs or disability) must be insufficient to meet the MIS for that household. The MIS is adjusted for islands and remote rural and remote small town locations.	21 °C in living room and 18 °C in other rooms for 9 hours each weekday, and 16 hours a day at weekends. This is adjusted for households as ministers deem appropriate allowing for 23 °C in living room for 16 hours a day for every day.

these conditions, but rather on their relationships to other conditions such as employment. Research which has used a metric has been categorised using the framework from Lucas et al. and is discussed below (Lucas et al., 2016).

5.2.2.1. Transport affordability. We adopt the definition of affordability from Lucas et al. that: the necessary weekly amount spent on transport leaves the household with a residual income below the official poverty line (Lucas et al., 2016). However, this definition is relatively novel and not widely adopted yet. With this in mind, all studies that concern the affordability of transport are considered in this subsection (Tables 8–10).

Just as with fuel poverty, individuals may suppress their transport costs in order to meet other needs (Lucas et al., 2016). However, unlike fuel poverty which has rigidly defined heating standards, it is much harder (and likely varies by household) to define a required "necessary" standard of transport and so income based metrics alone are likely insufficient measures of transport poverty. Indeed, equity in the case of transport would require focusing on outcomes, such as access to services, which is the focus of measures of accessibility. Problems are likely to arise, however; to take an extreme example, people who deliberately choose to live in remote areas far away from access to services may live in less equitable circumstances than those in urban areas according to a metric focused on the services they can access, and yet, in this case, this is their choice and they may not consider access to these services to be required.

5.2.2.2. Measures of mobility. Mobility poverty is considered to be a systemic lack of transport options. This draws on points 1 and 5 that: “*1) There is no transport option available that is suited to the individual's physical condition and capabilities;* and *"5) The prevailing travel conditions are dangerous, unsafe or unhealthy for the individual.*”

Note that “mobility poverty” as a search term does not yield many results (ten at the time of data collection). Additionally, mobility measures tend to focus on the "trip" and various characteristics such as generation and length (Lucas et al., 2016). Equity with regards to mobility poverty is an easier consideration than that of transport affordability, when examining definitions 1 and 5, we see that for an equitable outcome, neither condition should exist.

5.2.2.3. Measures of accessibility. Accessibility poverty considers whether people can reach destinations within reasonable time, ease, cost. This draws on: “*2) The existing transport options do not reach destinations where the individual can fulfil his/her daily activity needs, in order to maintain a reasonable quality of life";* and "*4) The individual needs to spend an excessive amount of time travelling, leading to time poverty or social isolation*”.

As with mobility poverty, we see that for an equitable outcome, the opposite of the mobility poverty definition must apply. However, we can critique both the use of "excessive time spent travelling" as this is in essence arbitrary, and "reasonable quality of life" as this is highly subjective.

5.2.2.4. Composites. A composite metric combines one or more measures of affordability, mobility and accessibility. These metrics attempt to combine one or more measures of transport poverty, but are subject to all the weaknesses of the individual sub-metrics. Other than the two studies shown in Table 11 this literature review has found no attempts to unify transport poverty metrics.

5.3. Lacunae and critiques

5.3.1. Energy poverty

A common critique across UK (expenditure) indicators is that they require modelled energy use using very UK specific data (the BREDEM model is a UK model), and also that assumptions which are baked into models do not always reflect actual household behaviours, (e.g. cultural differences in use of rooms) (Sovacool et al., 2021a, 2021b). In other words, we can only be so accurate about actual behaviour from these data. This data is not gathered outside the UK and thus studies outside the UK tend to use actual expenditure. This actual expenditure data, nevertheless, presents the disadvantage that households in fuel poverty

Table 7
Of minor and study specific energy and fuel poverty metrics.

Study	Metric/Method	Terms of reference as described at source	Commentary
Department of the Environment, Transport and the Regions (1996)	10% indicator	Fuel poverty (whole house energy usage)	Adapts Boardman (1991) with the following additions: 1) requires satisfactory heating; 2) Adds housing benefit and income support for mortgage interest to basic income - this is now "full income"
Sefton and Chesshire (2005)	10% indicator	Fuel poverty (whole house energy usage)	In addition to the Department of the Environment, Transport and the Regions (DETR) revision of the 10% metric, this report edits income calculation to include benefits and omits council tax from "full income"
Waddams Price et al. (2012)	Subjective fuel poverty	Fuel poverty (whole house energy usage)	Defines a subjective measure of fuel poverty, using a survey to ask households if they feel fuel poor
Thomson and Snell (2013)	Fuel poverty	Fuel poverty (whole house energy usage)	Adaptation of Healy and Clinch methodology using updated EU-SILC data to provide most up-to-date cross European fuel poverty comparison (Healy and Clinch, 2002).
Fabbri (2015)	Building fuel poverty index	Fuel poverty (whole house energy usage)	Composite index comprised of income, energy prices and building energy performance certificate
Walker et al. (2015)	Fuel Poverty Risk Index	Fuel poverty (whole house energy usage)	Fuel poverty risk index based on heating burden, built environment vulnerability, and social vulnerability
Wang et al. (2015)	Energy poverty comprehensive evaluation index	Energy and fuel poverty	Composite of many metrics covering access to energy (energy poverty) and affordability of energy in the home (fuel poverty).
Simoes et al. (2016)	Fuel poverty potential	Fuel poverty (whole house energy usage)	Creates fuel poverty potential metric using data on: income; education; unemployment rate; number of inhabitants above 65 years old; and both the space heating and cooling gap estimated for each housing archetype
Llera-Sastresa et al. (2017)	Index for household energy vulnerability assessment	Energy poverty (whole house energy usage)	Assesses vulnerability to energy poverty as a function of: dwelling energy performance; appliances energy performance; cost of energy; household energy consumption characteristics.
Okushima (2017)	Multidimensional Energy Poverty Index	Energy poverty (whole house energy usage)	Accounts for household energy cost, and energy efficiency of dwelling. A threshold is defined for each component, and thus the dimensionality of "energy" poverty is captured.
Aristondo and Onaindia (2018)	Energy poverty	Energy poverty (whole house energy usage)	Adapts Healy and Clinch metrics (Healy and Clinch, 2002), using a "counting poverty" approach from microeconomic studies of exclusion (Chakravarty and D'Ambrosio, 2006).
Bouzarovski et al. (2019)	Multidimensional Energy Poverty Index	Energy poverty (whole house energy usage)	Creates a composite of 5 measures: the low income high costs (LIHC), high energy expenditure, inability to meet heating standard, housing faults, and inability to pay utility bills.
Gouveia et al. (2019)	Energy poverty vulnerability index	Energy poverty (whole house energy usage)	Combines 2 sub-metrics: dwellings' energy performance gap, estimated using the buildings' energy demand and consumption; assessment of the population's ability to implement alleviation measures. These are used to form the energy poverty vulnerability index calculation for each of space heating and cooling
Ntaintasis et al. (2019)	Energy poverty	Energy poverty (whole house energy usage)	Uses multiple metrics in conjunction: required energy consumption for given building types; income and expenditure on energy; and survey of subjective fuel poverty, health conditions and impact of financial burden of energy on other household needs.
Castaño-Rosa et al. (2020)	Index of vulnerable homes	Energy poverty (whole house energy usage)	This method combines the factors of monetary poverty, energy and comfort indicators and household health to generate a composite vulnerability index. This is an attempt to combine technical and social aspects of households.

can moderate their energy expenditure i.e. households do not actually meet the required need, and so their actual expenditure is artificially low. Estimates for "actual" versus "required" expenditure in the UK show that households tend to spend only two thirds of what is required to meet set heating standards. This spending gap was noted by the Hills report and formed part of the rationale behind the fuel poverty gap sub-metric (Thomson et al., 2017a) (Hirsch et al., 2011) (Hills, 2012).

A second critique common to expenditure measures is that whilst a standard is defined for heating, no standard is defined to the quantity or quality of other energy services in the home, and additionally, summertime cooling is frequently ignored. With regards to heating standards, a point worth noting is that historically, the British are considered to have preferred colder homes, and thus, did not aim to build houses that were energy efficient, however; this is no longer the case today (Bouzarovski and Petrova, 2015) (Thomson et al., 2019) (Rudge, 2012).

The 10% Boardman threshold is based on 1988 data for expenditure on fuel (Boardman, 1991). Yet, this threshold has carried into the future and has not been updated to account for changes in incomes and energy expenditure since. Today, this threshold appears arbitrary, despite challenges against this arbitrariness and the critique that when adopted by the 2001 UK Fuel Poverty Strategy, this previously relative (twice contemporary median) measure became an absolute measure. This expenditure is "required" expenditure, thus being a more meaningful indicator of fuel poverty by ignoring actual household expenditure priorities (Liddell et al., 2012). The 10% indicator has also been criticised for being appropriate to England, but not the other constituents of the UK, by not reflecting their local twice-median expenditures. For example, Northern Ireland which has a high home energy expenditure due to reliance on home heating oil, and thus less efficient boiler technology (Liddell et al., 2012). Lastly, a typical criticism of the 10% indicator is that households which over-consume energy but are not adversely affected by the financial burden can be classed as energy poor (Liddell et al., 2012) (Moore, 2012) (The 2017 Scottish Fuel Poverty Definition Review Panel, 2017). Despite issues with the 10% metric, Liddell et al. state that this should be retained across all regions, for the purpose of comparison across the UK (Liddell et al., 2011).

Prior to the Hills definition, incomes were not equivalised (equivalisation is used to recognise economies of scale in household energy consumption). However, this critique has been recognised, and equivalisation has now been widely adopted (Herrero, 2017). The low income high costs (LIHC) indicator has been criticised for causing an opposite problem to the 10% indicator: namely that those with either very low incomes or small properties are not classified as fuel poor provided their energy costs are lower than the national median, regardless of how much hardship this financial cost causes.

Furthermore, the LIHC indicator itself is insensitive to fuel prices, the effects of which are only visible in the "fuel poverty gap" supplement i.e. it is not visible in headline data (Middlemiss, 2016) (The 2017 Scottish

Table 8
Listing transport affordability metrics.

Study	Metric/Method	Commentary
RAC Foundation (2012)	10%	Where more than 10% of (household) expenditure is used on transport (both personal and public). Note this unit of measurement is the household, not the individual, in contradiction with the assertion that individuals rather than households experience fuel poverty
Lovelace and Philips (2014)	Commuter fuel poverty (10%)	Measuring the proportion of a population spending more than 10% of their income on work travel
Mattioli et al. (2016)	Car-related economic stress (CRES)	An individual experiences car related economic stress if: 1) their equivalised income after housing and running motor vehicles costs is below 60% of the median 2) the percentage of income spent on running motor vehicles is more than twice the study's sample median (9.5%)
Mattioli (2017)	Forced Car Ownership (FCO)	A household in FCO is a household which owns "*at least one car and ii) reports difficulties to afford at least one of five items (rent, mortgage, household maintenance, energy bills, and food)*". This metric emphasises the ownership of a car over expenditure on car based transport (e.g. taxis).
Chatterton et al. (2018)	Motoring expenditure	Adds vehicle excise duty to fuel costs at vehicle and aggregate area level. These costs are then mapped geographically and then compared to median income. Note this paper also compares motoring expenditure to household gas and electricity bills.
Mattioli et al. (2018)	CRES (2)	Using fuel poverty as an analogy, this paper adapts the LIHC indicator for car expenditure, and defines the CRES gap in line with the fuel poverty gap

Table 9
Listing mobility poverty metrics.

Study	Metric/ Method	Commentary
Salon and Gulyani (2010)	Travel choices	This study uses a survey to determine the travel choices of slum residents in Kenya, noting that their choices are severely constrained by barriers to mobility options.
Tao et al. (2020)	Activity space	This study has developed the activity space as a composite of "*standard distance circle (SDC), the total distance travelled (TDT), the number of geographic locations visited (NGL) and the number of unique activity places (NAP)*"

Table 10
Listing accessibility poverty metrics.

Study	Metric/Method	Commentary
Shen (1998)	Accessibility index	Accessibility computed as a function of employment opportunities at given destination; an impedance function between two locations; number of job seekers in a given location; proportion of households in a location with access to one or more cars.
Gomide et al. (2005)	Synthetic index of adequate service	Index measuring urban poor access to public transport in Brazil, comprised of: average monthly expenditure on transport; walking distance to nearest bus stop; average headway; average travelling time; reliability of service; capacity; security and safety.
Currie et al. (2010)	Transport disadvantage	Uses a quantitative research survey and other available data to study transport disadvantage, and the impact of a lack of public transport options.
Kamruzzaman and Hine (2012)	Rural activity spaces	Measures transport activity spaces using activity travel diaries.
Department for Environment, Food and Rural Affairs (2018)	Overall measure of accessibility of services	For each Lower Layer Super Output Area (LSOA), an accessibility index is calculated by indexing and weighting the minimum travel times to key services (e.g. healthcare, education). Note these travel times are modelled rather than actual.
Allen and Farber (2019)	Transit access to employment	Uses competitive access to employment equations from economic literature to calculate: measure of a locations access by transit; measure of a locations access by car; and the number of workers in a catchment area for a given work location.
Benevenuto and Caulfield (2020)	Spatial Accessibility Poverty (SAP) indices	Gravity-based models proposed based on travel impedance methods derived from i) Friction surface datasets, and ii) Kernel density maps

Table 11
Listing composite transport poverty metrics.

Study	Metric/Method	Commentary
Sustrans (2012)	Composite risk of transport poverty index	Comprised of: "*1) households that would need to spend 10% or more of their income on car running costs 2) people living more than one mile from nearest bus or station 3) number of essential services that would take more than 1* hour *to access by walking, cycling and public transport*"
Berry et al. (2016)	Composite	Composite indicator including financial resources, mobility practices and conditions of mobility

Fuel Poverty Definition Review Panel, 2017). Other critiques of LIHC include the political aspects: the policy of 'helping those most in need' is considered to be an abdication of responsibility by the UK Government, highlighting a shift in perspective from believing fuel poverty can be eradicated to a belief that it can only be alleviated, and it is postulated that this new political attitude reinforces the relationship between poverty and fuel poverty. Indeed, it is believed the indicator was adopted to show the number of people living in fuel poverty is now stable over time (even when there are large changes in energy markets) and the UK Government has been able to alleviate the condition, though as previously stated, on the other hand this insensitivity would suggest LIHC is not a valuable indicator. In a further political critique, under the LIHC indicator those with low housing costs are at a higher risk of being in fuel poverty, yet fuel poverty is not a consideration in housing policy (Middlemiss, 2016).

Consensual measures such as that of Healy and Clinch are less complex than expenditure measures, which can be both an advantage and disadvantage: data are less complex to collect and cross country studies can be carried out using the same survey. However, different cultural interpretations of thermal comfort, and what different individuals and cultures value spending on can skew results (e.g. the use of air conditioning in summer). Furthermore, Boardman notes those in fuel poverty can live in denial of their condition (Healy and Clinch, 2002) (Bouzarovski, 2013) (Boardman, 2011). In favour of consensual measures, Healy and Clinch level a criticism that UK income methodology is confusing, that multiple methods for calculating incomes exist, and these are not necessarily transferable to other countries. There is also debate as to what should be included in incomes (e.g. how benefits are captured), which will in turn vary across countries (Healy and Clinch, 2002).

Minimum Income Standard (MIS) approaches have been adopted into the recently updated Scottish definition of fuel poverty, but have not otherwise widely appeared in the literature this review surveyed, and are thus not widely critiqued (The 2017 Scottish Fuel Poverty Definition Review Panel, 2017). In the Scottish context, the MIS approach is used to adjust income for required expenses such as childcare.

Recently, Mahoney et al. have advocated for the creation of a single cross-UK indicator to enable fair comparison across the UK's countries, arguing that the lack of fair comparison is fostering regional inequalities (Mahoney et al., 2020). However, while this comparison may be useful, one indicator alone has repeatedly been deemed insufficient for measuring fuel poverty. Recommendations to overcome limitations of a single indicator include developing new regional specific indicators such as a local severity index, using a combination of those indicators that already exist, and using vulnerability frameworks to assess multiple characteristics of the fuel poverty condition (Liddell et al., 2011) (Herrero, 2017) (Thomson et al., 2017a). Therefore, whilst an indicator could be developed for cross-country comparison, it is unlikely that such an indicator would reflect all of the nuances of local situations everywhere it would be applied.

Given the inadequacy of single measures, composite indicator studies have begun to emerge. Some have assigned weights to subjective measures such as Nussbaumer et al., and others have used expenditure measures in composite with subjective measures such as Ntaintasis et al. (Nussbaumer et al., 2012) (Ntaintasis et al., 2019). These composite indicators are generally considered superior to single indicator studies by compensating for the weaknesses of any single indicator (O'Sullivan et al., 2015) (Ntaintasis et al., 2019). Yet, these composites are still missing other risk factors for fuel poverty when we consider Baker et al.'s proposition to "*rethink fuel poverty as a complex problem*". Baker et al. propose to rethink the Boardman definition as a risk metric to also the following factors: 1) household debt; 2) poor heating regime; 3) poor indoor quality; 4) poor mental health; 5) poor physical health; 6) low educational attainment. These should be additional to the Boardman factors of high fuel costs, building energy performance, high fuel costs and poor housing quality. They propose that not just those in fuel poverty, but also those at risk of falling into fuel poverty should be considered (Baker et al., 2018). Mental and physical health aspects have been identified in Thomson et al.'s vulnerability framework, but are rare elsewhere in the literature (Thomson et al., 2017a). The link between educational attainment and fuel poverty has not been examined in fuel poverty metrics covered in this review. Lastly, Travellers and other transient populations are very often missing from data due to the inherent difficulties in collecting such data (Herrero, 2017). As such, they are hence neglected from fuel and energy poverty indicators.

In summary the following critiques apply to some or all fuel poverty metrics;

1. The definition changes the problem scale,
2. A combination of metrics is better than a single metric,
3. Extra factors should accompany fuel poverty metrics such as health indicators and household debt measures,
4. Summertime cooling has been overlooked in the fuel poverty debate in the UK, which will become increasingly problematic in a future of warmer summers,
5. Data is a frequent limitation,
6. Heating standard is often defined, yet fuel poverty now also refers to all household energy use. Standards for appliance usage etc. have not been defined,
7. The chosen poverty line is essentially arbitrary,
8. It is very rare for actual energy use to be equal to required energy use.

The next step in fuel poverty research will be to address data gaps such as those identified by Thomson et al. and also to incorporate further risk factors as identified by Baker et al. (Thomson et al., 2017a) (Baker et al., 2018). Further consideration must also be given to actual versus required energy use due to differing perceptions of thermal comfort.

5.3.2. *Transport poverty*

There is no standardised definition of transport poverty in the literature so critiques of it are rarer and less developed. Attempts to create a common set of definitions have been made, yet the literature more widely has been slow to coalesce to this common set. As such, this review adopts Lucas et al.'s transport poverty definitions to create consistency with the literature per their recommendations (Lucas et al., 2016). As there is no homogenized definition of transport poverty, there are no standardised metrics of transport poverty. This lack of standardisation is also visible across countries as different countries collect different data.

Using the analogy of fuel poverty, expenditure measures such as the 10% indicator have been adopted, for example, by the RAC Foundation. However, the finding that four fifths of British households live in transport poverty has been criticised for including non-essential transport such as holidays, and thus, is considered to be an implausibly high figure, devaluing the debate on actual transport poverty (Campaign for Better Transport, 2012a). Meanwhile, the adoption of the 10% threshold has been criticised for being too low as the average British household expenditure on transport was 14% of income at the time (Campaign for Better Transport, 2012b). Therefore, we see the difficulty with expenditure threshold metrics in this field.

Researchers have indicated that better data would lead to better metrics, but it would have to be very specific to the metric developed. This, however, presents a chicken and egg problem, we will only truly know how good a metric is once we have developed and tested it. As with fuel/energy poverty, we need a metric or multiple metrics from each subfield, which could then be combined in order to gain a more complete view of transport poverty.

Banister (2018), in an engineering context has recognised the accessibility and cost aspects which are well represented in the transport poverty literature discussed in this review. Not explicitly acknowledged by transport metrics, but rather implicitly considered (e.g. in discussions of equity), Banister has furthermore devoted considerable time to the study of transport inequality. Banister (2018) has introduced indices to measure inequality across income groups in the UK to consider trips by mode, trips by distance and trips by travel time, finding significant disparities between higher and lower income deciles in the former two, and less pronounced differences in the latter category (except for very long distance trips, where perhaps unsurprisingly high income groups take many times more such journeys than lower income groups) (Banister, 2018). The assessment of inequalities as conducted in this engineering literature (where otherwise studies are typically concerned with solving such problems) in conjunction with assessments of transport poverty is an area of opportunity in the transport poverty literature.

6. Mapping new dimensions of vulnerability

The notion of unifying the study of fuel and transport poverty is a recent one. Mattioli et al. outline some recent literature concerning the

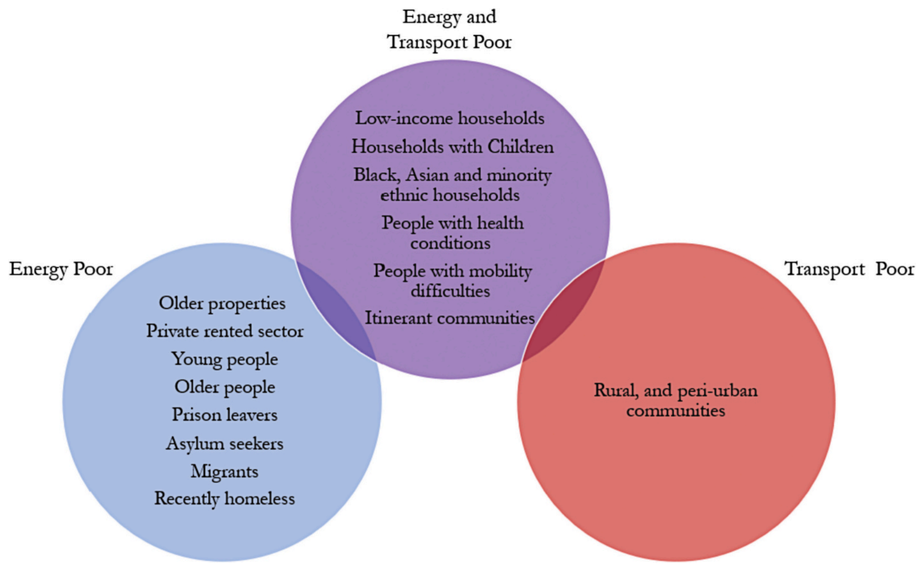

Fig. 15. Adapted from Simcock et al. (2020) showing the demographic groups vulnerable to energy and transport poverty.

justice implications of the expected energy transition (Mattioli et al., 2017). In simplistic terms, the shift from ICE cars to EV cars is problematic for the fuel and transport poor, who can neither afford the higher price of purchase nor the increase in domestic energy consumption required to "refuel". In other words, a technology swap alone is highly problematic. This is before we consider whether the continued mass use of private cars is desirable from a justice perspective or not.

The idea of combining the measurement of fuel and transport poverty is no mean feat. As Mattioli et al. note "*Notably, metrics come with a set of assumptions and their own (policy) history… the importance of these contradictions will become increasingly evident and problematic.*" (Mattioli et al., 2017) These contradictions are: differing units of analysis (household vs individual), (modelled) required vs actual spend, affordability threshold and (exclusive to LIHC) the a-priori exclusion of non-poor households. Furthermore, it has been identified that a required standard of heating is expressed in fuel poverty definitions but not in transport poverty definitions.

Berry et al. have attempted to apply multiple fuel poverty indices to the problem of transport poverty, culminating in a composite indicator comprised of: financial resources; mobility practices; and conditions of mobility, after noting that fuel poverty indicators don't take account of "*(1) the diversity of travel needs, (2) restriction behaviours, and (3) variable capacities to adapt*" (Berry et al., 2016). Berry later expanded on this by combining the following indicators for each of housing and transport: restriction, housing/mobility conditions, equipment, energy spending, and standard of living. If a household meets a threshold number of factors it becomes classed as energy poor, with the severity determined by number of factors (Berry, 2018). This metric shows only partially overlapping results with those identified as energy poor using budget threshold measures alone, and thus illustrates how existing income based metrics can inadvertently misdirect policy support. These composite indicators are the only indicators this review has found which unite fuel and transport poverty. Recently, research has shed light on the groups vulnerable to and affected by fuel and transport poverty:

The groups considered to be vulnerable to both conditions are listed in the purple circle, continuing the application of vulnerability lenses from earlier research (Bouzarovski, 2013) (Bouzarovski and Petrova, 2015). This however, neglects groups such as Irish Travellers as we have noted and other transient populations as previously remarked (Herrero, 2017) which we have added to Fig. 15. Note these categories are not mutually exclusive, i.e. one obviously may be both an older person and live in a low income household. We consider vulnerability lenses to be a vital additional tool. Excessive use of metrics can lead to policy focused on these metrics, and may ignore actual outcomes arising from the insufficiency of metrics.

Yet achieving equity in the future joined energy-transport system will require more than the alleviation of energy and transport poverty. Standards in each area may be necessary, yet these do not exist in either the energy requirements of a household outside of heating, nor in transport. A minimum living standard of both conditions (which may trade one area off against the other) is required to enable the full participation of households and individuals in society. However, given the difficulties with stipulating a standard of travel, this minimum living standard should be cognisant of both the "complexity" of both problems and the agency of individuals who may reject the idea of living in a condition of "poverty". Therefore, these standards ought not to be rigid or purely quantitative, but may rather comprise a framework combination of holistic and measured assessments. In short, we can see that the following issues apply to combining metrics in energy and transport poverty;

1. A combination of metrics is better than single metric in both energy and transport poverty,
2. Extra factors should accompany energy poverty and transport poverty metrics such as health indicators or air pollution data,
3. Data is a limitation across both sets of metrics, whilst the design of metrics and data collection presents a chicken and egg problem,
4. Assessing who is vulnerable to each condition is less fraught with technical difficulties than attempting a quantitative measure,
5. A combination of vulnerability lenses and composite or multiple energy and transport poverty metrics are welcome.

Furthermore, we have noted an absence of study on the overlapping services provided by energy and transport (e.g., in a future energy system, an EV may provide both transport and electricity for domestic consumption). A comprehensive assessment of these factors may provide another means of assessing vulnerability and an avenue towards the defining of standards overlapping both conditions.

Based on the state of the art literature review we recommend that social science, econometric and engineering concepts be integrated innovatively to capture the breadth and depth of energy and transport poverty, with a view to guiding decarbonisation pathways along fair routes, whilst attempting to tackle the competing technical, operational, and administrative issues which arise when considering these issues.

7. Conclusion

This study has conducted a bibliometric review of fuel/energy poverty and transport poverty and a systematic review and critical content analysis of metrics in these fields. We have seen that the fuel and energy poverty literature have been largely separate areas of study until recently, whilst transport poverty is an area of scant research. Limitations exist when searching the academic literature for transport poverty: firstly, that user knowledge of very specific search terms is required, biasing the results, and secondly, that much work in this area lies outside of the academic literature. The same limitations cannot be said to apply to fuel and energy poverty. Fuel and energy poverty are slowly coalescing towards a common definition, and as stated, we recommend the shift away from the term fuel poverty, so that measurements of this condition can be used to achieve more equitable outcomes.

Existing reviews have highlighted the flaws of metrics in these fields, which we have re-examined from the perspective of equity. We find that old critiques such as data limitations still apply, and remain difficult to overcome. Some work has commenced on the unification of metrics in energy and transport poverty; this will be essential for the future measurement of these conditions as the energy and transport systems integrate. These composite metrics should be explored further in different countries and contexts, and further factors such as monitoring educational outcomes should be incorporated such that this work becomes "complex". This is no mean feat and will require energy and transport poverty research to do more than just pay lip service to interdisciplinarity. In this regard, this future work will strive to integrate the study of energy and transport poverty from the social sciences into the engineering disciplines to break down discipline silos and operationalise change.

Not only must composite metrics be further explored, but a further examination of the overlapping services from energy and transport is needed for equitable outcomes in the future energy-transport system. These should recognise each issue as a complex problem and respect the rights of individuals. Another area of research has considered who is vulnerable to the conditions of energy and transport poverty. Again, these are only as useful as the data collected and thus, currently neglect transient populations such as the travelling community. Additional lenses such as an examination of overlapping energy and transport services are welcome and indeed should be layered on top of existing lenses and metrics. For immediate policy purposes we recommend the shift away from relying on single indicators. For example, the reliance in England on the LIHC indicator alone has serious drawbacks such as omitting people with very low incomes (and costs below the median); this can exacerbate the very condition the metric seeks to alleviate.

Finally, as regards to this research moving forward, the review will be used to inform and operationalise energy and transport poverty metrics whilst acknowledging the energy quadrilemma of environmental protection, social equity, economics, and energy security in the form of a *techno-enviroeconomic* analysis to close the energy and transport poverty gap; supporting policy aims to become reality on the ground. This will be achieved by interlinking of multiple metrics and lenses to analyse the impacts and effects of technical solutions on different social demographics, and the energy and transport sectors.

Disclaimer

The views and opinions expressed in this paper do not necessarily reflect those of the Northern Ireland Department for the Economy or the European Commission or the Special EU Programmes Body (SEUPB).

Declaration of interests

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Appendix A. Supplementary data

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